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Investigation of refractive index profile induced with femtosecond pulses into neodymium doped phosphate glass for the purposes of hybrid waveguiding structures formation

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Abstract

The technique of writing depressed cladding waveguides into Nd:phosphate glass with relatively large mode field diameter in 2-line geometry was reported for the purposes of waveguiding structures formation. The easy to use and accurate technique of induced refractive index measurement was proposed, and it was shown the inefficiency of widespread indirect (numerical aperture) technique of refractive index measurement for such femtosecond written waveguides.

Keywords: waveguide; femtosecond writing; refractive index; integrated optics; ultrafast micromachining

1. Introduction

Direct femtosecond laser writing is a widespread technology for waveguides formation inside transparent optical materials. This technique provides fast production of different photonic devices and optical integrated circuits

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[Osellame et al. (2012), Okhrimchuk et al. (2005)], combining advantages of both solid-state and optical fibers technologies. Rare earth doped phosphate glass is one of the most active optical materials. It should be noted, that induced refractive index is negative in this material. Thus, to form a waveguide it is necessary to form depressed cladding rather than core with increased refractive index. Depressed cladding waveguides are of the great interest for glass amplifiers [Thomson et al. (2006)], which maintain their original spectral properties of core region after inscription process. The majority of depressed cladding waveguides have asymmetric cross section [Okhrimchuk et al. (2005), Homoelle et al. (1999), Quang An et al. (2014)] and it is complicated to measure the value of induced refractive index after inscription. Therefore, preliminary investigation of single induced tracks is the key aim before design and formation of induced waveguides. There is a number of techniques to measure refractive index distribution, such as: interferometry methods and refracted near-field (involve complicated equipment), quantitative phase microscopy and Z−scan techniques (easy to use, described in the paper), relation between numerical aperture (NA) and core-cladding refractive index difference (low accuracy for gradient waveguides) and chemical etching followed by profilometry (involve complicated absolute calibration for each material). For the purposes of femtosecond inscription easy to use and accurate method of permanent induced refractive index measurement is required. Quantitative phase microscopy followed by Z−scan technique is suitable for the purpose. In this paper we investigate phase structures induced with tightly focused femtosecond laser emission in such material of great practical importance as Nd:phosphate glass. The examined range of conditions is achieved with commercial lasers, but it is poorly investigated yet.

2. Experimental setup

Optical waveguides were written in the experiment following the well-known transversal scheme (see. Fig. 1) utilizing femtosecond laser (Fianium, FP060-PP-s) with pulse duration 450 fs, 1060 nm central wavelength and 1 MHz pulses repetition rate. The long length structures with induced refractive index were inscribed inside neodymium doped phosphate glass samples ($n_{Nd} = 7.4*10^{20}$ cm^{-3}, LFS4-7.4, LZOS). The laser beam was focused 1 mm below the sample surface by aspheric lens L1 (see Fig. 1) and long-focus lens L2, which additionally increases divergence of laser beam and, thus, the focal spot diameter. The following diameter of focal spot within the sample was nearly 7 micron. The sample was moved with computer controlled translation stage at translational velocity of 0.8 mm/s in such a way that induced waveguides were written through the overall length of the sample (3 cm). Polarization of laser was kept parallel to the writing direction. The energy of laser pulses inside the sample was 470 nJ (and additional 300 nJ was concentrated in more than 2 ps pulse pedestal).

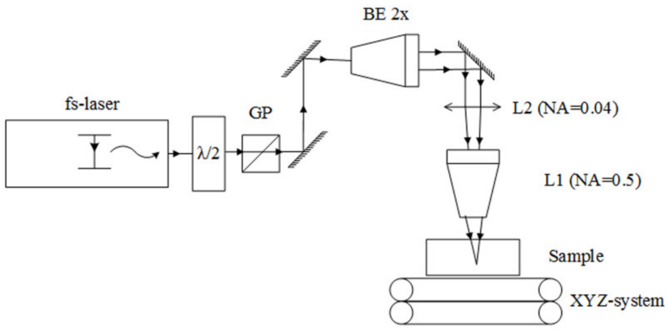

Fig.1. Schematic of experimental setup. GP – Glan prism, BE 2x – beam expander, L1 (aspheric) and L2 (long focus) – focusing lenses, XYZ – multi-axis positioning system.

The cladding of the waveguide was formed by 2 parallel tracks along the sample with 25 micron gap between them (see Fig. 2). Each track of the cladding was written with 2-lens system for increase the aspect ratio and size of the structure in the direction of laser beam. Writing energy maintained below dramatic optical breakdown to prevent cracks formation and corresponding scattering of light.

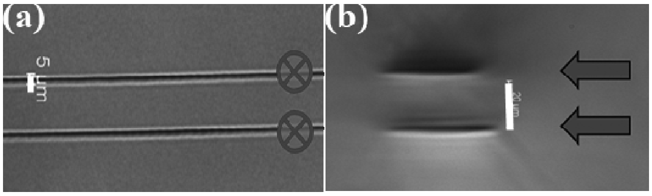

Fig.2. Photographs of the waveguide induced in Nd:phosphate glass: from the side of writing beam (a) and from the orthogonal polished facet (b). Arrows represent direction of the writing beam.

3. Induced refractive index measurement procedure

To measure the profile of induced refractive index we implemented the combination of quantitative phase microscopy and Z-scan techniques. For determination of phase shift profile in relative units, we used inverse modeling of transport intensity equation (1) [Paganin and Nugent (1998)]:

$$-k\frac{\partial I(r_\perp,0)}{\partial z} = \nabla_\perp \cdot \left[I(r_\perp,0)\cdot \nabla_\perp \cdot \varphi(r_\perp,0)\right] \tag{1}$$

The numerical solution was based on three microphotographs of each induced structure: at the focus, 10 micron below and 10 micron upper the focus. The profiles were measured in two orthogonal projections to reconstruct two-dimensional distribution of induced refracted index in the cross-section of the extended structure. Reconstruction of refracted index distribution in absolute units was complicated by the fact that induced structures are highly asymmetric with aspect ratio about 6 (see Fig. 2). Thus, as it can be seen from standard QPM-technique for axial symmetric waveguides, applying of inverse Abel transform was limited.

To solve the problem of normalization it was proposed to use Z-scan procedure [Palfalvi et al. (2003)]. This technique provides relatively low spatial resolution (several microns), but enables to find absolute value of induced refractive index in the treated region. For experiment realization of the method long-focus lens was used with Rayleigh length compared to the length of induced structure. The experimental Z-scan curve than was fitted with analytical dependence for thin sample (2) [Palfalvi et al. (2003)]. To reconstruct the absolute distribution of induced refractive index, the profiles obtained with QPM-technique were normalized to the mean value, obtained with Z-scan procedure.

$$T\left(\frac{z}{z_0}\right) = 1 - \frac{4\cdot\left(\frac{z}{z_0}\right)\cdot\Delta\varphi_0}{\left[\left(\frac{z}{z_0}\right)^2+1\right]\left[\left(\frac{z}{z_0}\right)^2+9\right]} \tag{2}$$

4. Results and discussion

Characteristic Z-scan curve, obtained in experiment, is shown in Fig. 3a. The corresponding value of mean phase shift, according to the fitting, equals 0.5 radian. After normalization the induced refractive index profile across the structure was calculated and the result is presented in Fig. 3b. It should be noted, that all measurements were carried out for single induced track rather than fully-constructed waveguide with geometry showed in Fig. 2.

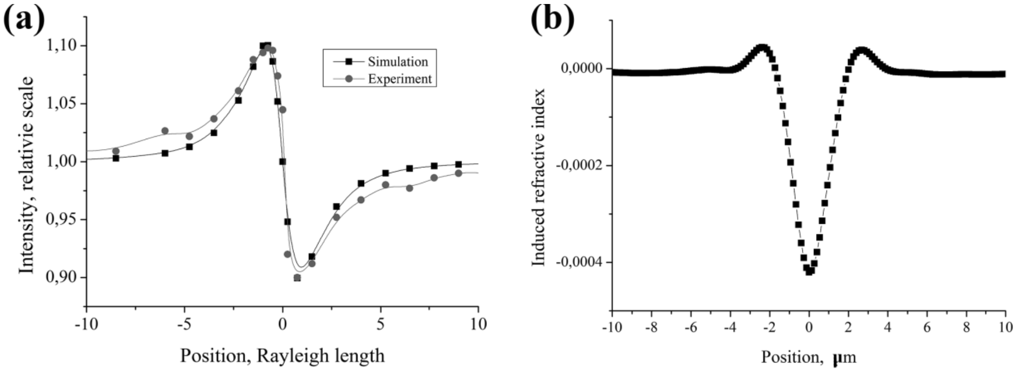

Fig. 3.Typical Z-scan curve (a) and induced refractive index profile (b).

As experiment demonstration of guiding properties of induced structures is shown in Fig. 4 simulated far field mode at 1-meter distance (a) and experimental propagating mode photograph (b) that are in agreement with each other. Due to the fact, that induced waveguide is anisotropic, the losses for orthogonal polarizations significantly differ: 0.6 and 1 dB/cm for horizontal and vertical polarization accordingly.

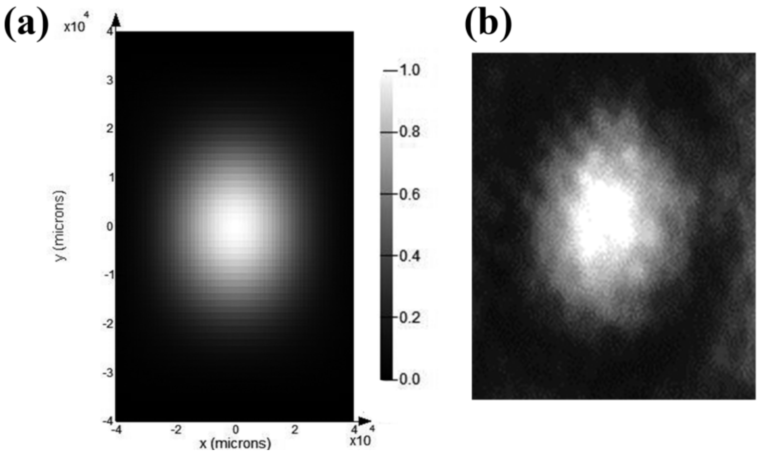

Fig. 4.Simulated far field mode at 1-meter distance (a) and experimental propagating mode photograph (b).

Finally, it should be noted, that such widely used [Homoelle et al.(1999), Qiang et al.(2014)] indirect technique of refractive index measurement as numerical aperture measurement is not applicable for such femtosecond written waveguides. The connection between numerical aperture of the waveguide and core-cladding refractive index contrast (3) is valid only for axial symmetric waveguides with step index profile, while femtosecond written waveguides always have smooth refractive index profile and sometimes have anisotropic cross section.

$$NA = \frac{\sqrt{n_{core}^2 - n_{clad}^2}}{n_0} = 0.01 - 0.03 \Rightarrow \Delta n = \frac{NA^2 \cdot n_0}{2} \approx 3 \cdot 10^{-4} \qquad (3)$$

$$\Delta n \approx 2 \cdot 10^{-3} \qquad (4)$$

In accordance with comparison below, the value obtained with NA measurement (3) is one order less than the one obtained with the proposed combined technique (4), which is also stands in accordance with numerical simulation of propagation modes (MODE Solutions, Lumerical Inc.).

5. Conclusions

In this work we have reported the technique of writing depressed cladding waveguides into Nd:phosphate glass with relatively large mode field diameter in 2-line geometry, which could be helpful for development of laser induced optical amplification components. There was proposed a combined technique of induced refractive index measurement. The technique is easy to use and provides both sufficient accuracy ($<10^{-4}$) and spatial resolution (<0.1 micron). It was also shown the inefficiency of such widespread indirect technique of refractive index measurement, which relies on the connection between numerical aperture of the waveguide and core-cladding refractive index contrast.

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References

Osellame, R., Cerullo, G., Ramponi, R., 2012. Femtosecond laser micromachining photonic and microfluidic devices in transparent materials, Springer, London.
Okhrimchuk, A.G., Shestakov, A.V., Khrushchev, I. and Mitchell, 2005. J., Opt. Lett. 30, 17, 2248-2250.
Thomson, R.R. et.al., 2006. IEEE Photonics Technology Letters 18, 14, 1515-1517.
Homoelle, D., Wielandy, S., Gaeta, A.L., Borrelli, N.F. and Smith C., 1999. Opt. Lett. 24, 18, 1311-1313.
An Q.,, Liu, H., de Aldana, J.R.V., Feng, C., 2014. Optics and Laser Technology 56, 382-386.
Paganin, D. and Nugent, K.A., 1998. Phys. Rev. Lett. 80, 12, 2586-2589.
Palfalvi, L., Hebling, J., Almasi, G., Peter A.and Polgar K., 2003. J. Opt. A: Pure Appl. Opt. 5, S280S283.